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The effect of vegetation on soil and ground water chemistry and hydrology of islands in the seasonal swamps of the Okavango Fan, Botswana

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Abstract

Evapotranspiration exceeds rainfall by a factor of three in the Okavango swamps of northern Botswana, yet saline surface water is rare. Brines develop in the groundwater beneath islands, however, and very strong lateral concentration gradients develop. These arise as a result of transpiration by trees which grow around the fringes of islands as well as by capillary evaporation of groundwater from the interior of islands. Precipitation of calcite and amorphous silica from the groundwater occurs beneath island fringes. Long-term monitoring of the water table and groundwater chemistry beneath an island in the seasonal swamps has revealed that groundwater rises and falls with the seasonal flood and that the saline groundwater remains centred beneath the island. The study shows that islands act as sinks for dissolved solids during intense evapotranspirational loss from the swamps.

1. Introduction

The Okavango Delta of northern Botswana (Fig. 1) is one of the largest alluvial fans on earth, with a total surface area in excess of 30 000 km^2. It has formed as a result of the discharge of the Okavango River into a graben at the southern extremity of the East African Rift system. The Delta lies on the edge of the semi-arid Kalahari Desert and annual rainfall is 500 mm while evapotranspiration is 1860 mm (Wilson and Dincer, 1976). However, discharge of the Okavango River is sufficiently large (11×10^9 m^3 year^{-1}) to sustain 6000 km^2 of permanent swamp and a further 6000–12 000 km^2 of seasonal swamp on the fan surface. The water is distributed through the swamps by a channel system (McCarthy et al., 1991a, 1992). The average gradient on the fan is

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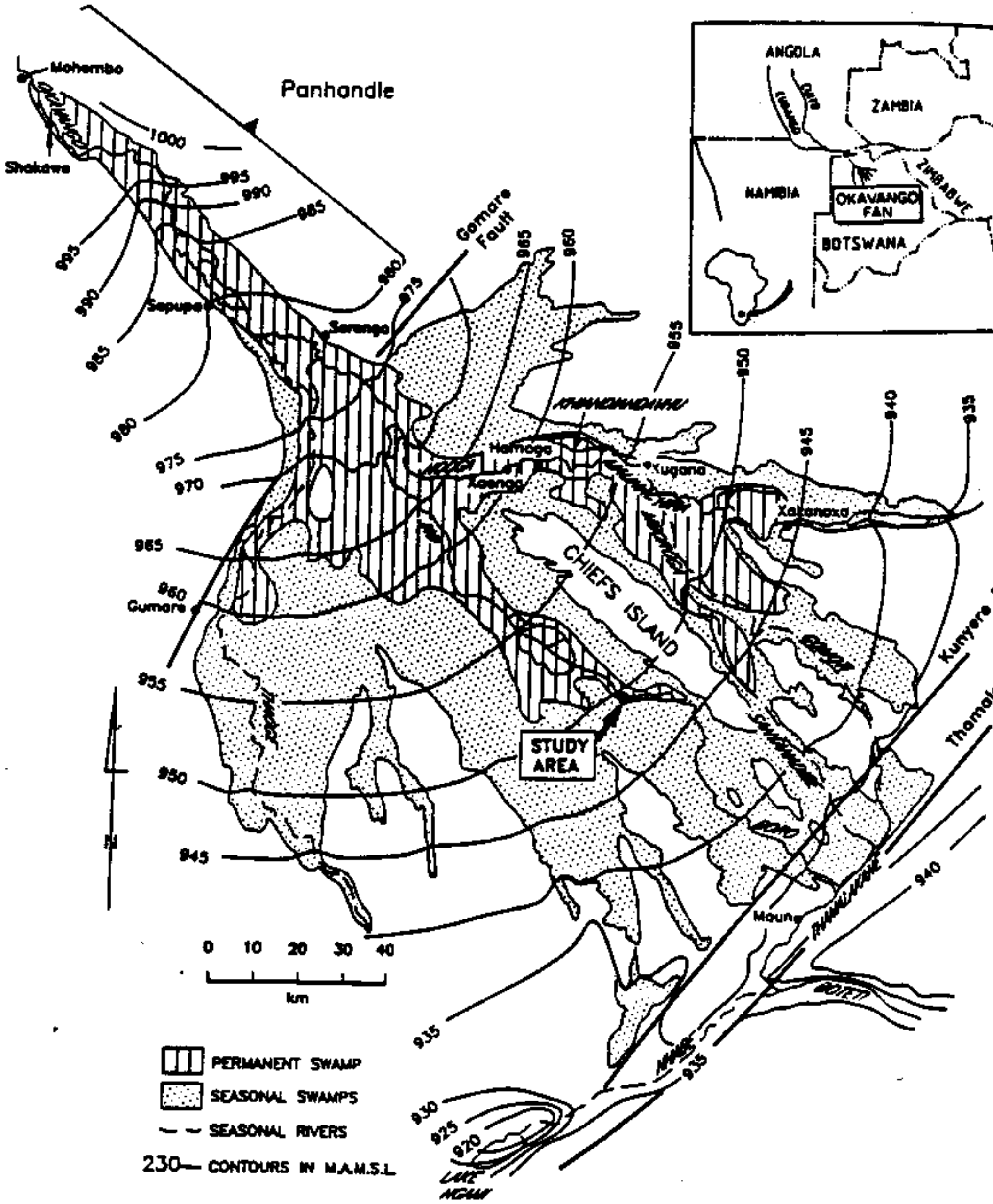

Fig. 1. The Okavango fan showing location of the study area.

about 30 cm km^{-1} and the topography is gently undulating, with local relief typically less than 2 m. Average water depth in the permanent swamps is about 1.5 m (Wilson and Dincer, 1976) and is probably less than 1 m in the seasonal swamps. The undulating topography and shallow water conspire to produce a vast archipelago across the fan, especially in the seasonal swamps. The islands are usually heavily vegetated with a variety of tree species, while the swamps support dense growth of sedges and grasses.

Okavango River water has a very low salinity (ca. 35 ppm TDS) which increases down fan to about 95 ppm in the outflow. Dissolved solids are dominated by silica and bicarbonates of Ca, Mg, Na and K. Only 2% of inflow plus rainfall (ca. 5×10^9 m^3 year^{-1}) leaves as surface flow because of the high evapotranspiration and a further 2% leaves as groundwater flow (Dincer et al., 1981). Mass balance calculations carried out by McCarthy and Metcalfe (1990) indicate that the total dissolved solid load entering the Delta each year amounts to about 400 000 t, but only about 30 000 t leaves in surface outflow. In spite of this, saline surface water is rare in the Delta. Islands have been identified as sinks for dissolved solids and the groundwater beneath these islands is very saline (McCarthy et al., 1991b, 1993).

Previous studies of the processes which lead to brine formation beneath islands were confined to the permanently inundated regions of the swamps (McCarthy and Metcalfe, 1990; McCarthy et al., 1991b, 1993; Ellery et al., 1993) where seasonal water level fluctuations are small (< 20 cm). It has been found that swamp water in these areas has very low TDS, with conductivities typically less than 100 μS cm^{-1}. The water table beneath islands is typically lower than that in the surrounding swamps and ground water salinity increases steadily from the island margins inwards, locally exceeding 10 000 μS cm^{-1} in the interior. Islands are usually fringed by a zone of broad-leaf evergreen trees, giving way to deciduous trees and palms, and eventually to sparse grassland and even bare soil in the island interiors. This zonation is a consequence of groundwater chemistry. The salinity gradients beneath islands are believed to be caused by transpiration by trees. The seasonal swamps which form the more distal reaches of the fan are subject to much greater seasonal water level fluctuations (> 1 m) yet vegetation on islands in these areas also shows zonation, suggesting that lateral chemical gradients exist beneath these islands as well. The present study was undertaken to examine the hydrological and chemical response of the ground water system to these large seasonal fluctuations in water level.

2. Study area

Seasonal water level fluctuations in the Panhandle region of the upper Delta (Fig. 1) are generally greater than 1 m but decline down the length of the Panhandle and in the permanent swamps of the upper fan, seasonal fluctuations are of the order of tens of centimetres. These rise again in the seasonal swamps and may exceed 2 m in the distributary channels. The transition between seasonal and permanent swamps is gradual and migrates with long-term (decadal) oscillations in rainfall in the catchment area of the Okavango River.

A study area was chosen in the upper reaches of the seasonal swamps, close to the Boro distributary channel and, for logistical reasons, the Xaxaba Safari

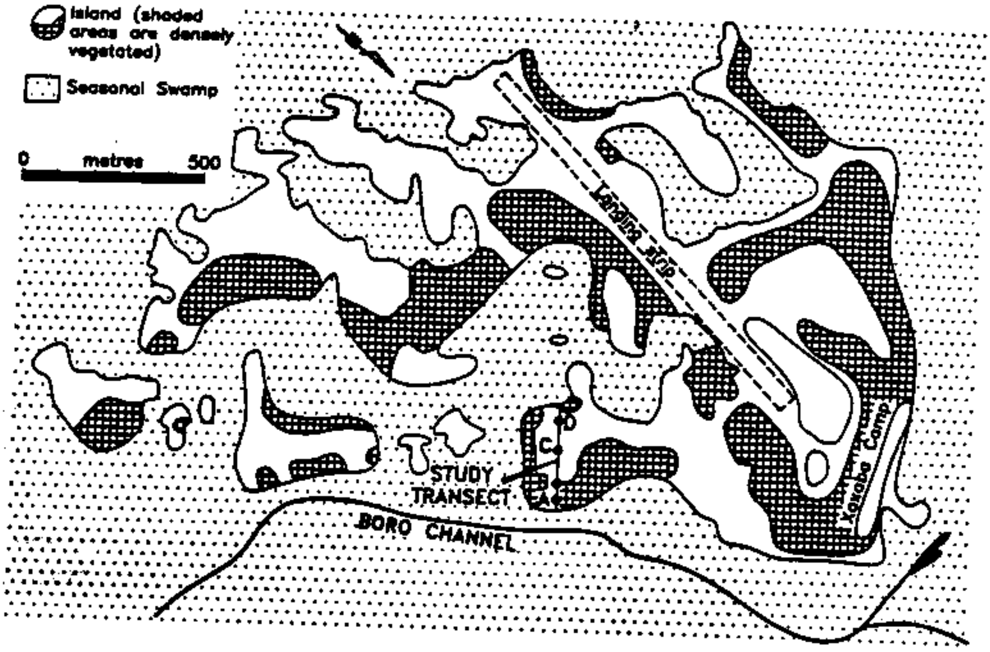

Fig. 2. Map of the study area.

Lodge (Figs. 1 and 2). The study site consisted of a semi-circular island connected to a larger, elongate island by a narrow isthmus. The study island was fringed by large trees while the interior supported only sparse grass cover and is typical of the islands which abound in the upper and middle reaches of the seasonal swamps.

3. Methods

3.1. Field studies

A transect across the island (Fig. 2) was topographically surveyed. Vegetation was recorded along the transect using an estimate of cover abundance, as described by Meuller-Dambois and Ellenberg (1974). The cover scores of 1–8 were assigned to intervals between 0.1, 2, 5, 10, 25, 50, 75 and 100%, respectively. Auger holes were made at regular intervals along the transect and soil samples collected for analysis. Depth to the water table was measured in each of these holes after allowing 24 h for groundwater to equilibrate. Water samples were collected from the auger holes and from the swamp for conductivity measurement and selected samples were subjected to full analysis using the methods described by McCarthy et al. (1991b). In addition, groundwater samples were collected at various depths below the water table at one location along the transect (site B) using piezometer tubes (plastic tubes fitted with sintered glass discs at the lower end). This was carried out to examine vertical concentration gradients in the groundwater. Soil samples were subjected to mineralogical analysis and partial chemical analysis (for CaO and MgO) using X-ray fluorescence spectrometry (McCarthy et al., 1991b).

Four sites along the transect (sites A–D) were chosen for long-term monitoring. This monitoring extended over a period of 17 months. At approximately monthly intervals during this period, new auger holes were made at each site, depth to water table was measured and a water sample collected. In addition, swamp water level was recorded and a water sample collected. Monthly rainfall at the site was also recorded. Twelve months after commencement of the programme, the entire transect was re-surveyed and the groundwater re-sampled. Finally, diurnal variation in the water table was examined by measuring depth to the water table at several sites over the course of a 24 h period. The field work and sampling was carried out between April 1991 and August 1992.

3.2. Model experiments

A physical model was constructed to assist in the interpretation of the groundwater hydrology. This consisted of a large, rectangular container with transparent Plexiglas sides (Fig. 3(A)). Several half-round, perforated tubes were glued to one of the Plexiglas sides and a removable perforated tube connected to an external stop-cock was installed along the bottom to serve as a drain. The container was half-filled with coarse sand (grain size ca. 0.7 mm), the surface of which was shaped into appropriate land forms. Coarse sand was used in order to reduce the thickness of the capillary fringe. The half-round tubes served to produce a free water surface below the surface of the sand so that the water table could be unambiguously defined. A branched, perforated tube device was constructed to simulate a tree with roots (Fig. 3(B)). The perforated end was buried in the sand and the top was connected to a suction system to model transpiration.

Three experiments were carried out using this model:

(1) The effect of transpiration on the water table beneath an island. In this experiment, the sand in the container was shaped into a 'half-island' section and the tree was buried in the island fringe (Fig. 4(a)). Water was added to the container so that some surface water was visible in the 'swamp'. Water was simultaneously removed via the 'tree'. The model was adjusted to reach steady state by balancing inflow and outflow and the water levels in the half-round tubes (the water table) were recorded.

(2) The effect of periodic flooding on the groundwater regime beneath an island in which water table draw-down results from transpiration. Water was added to the model, configured as above, so that a large amount of surface

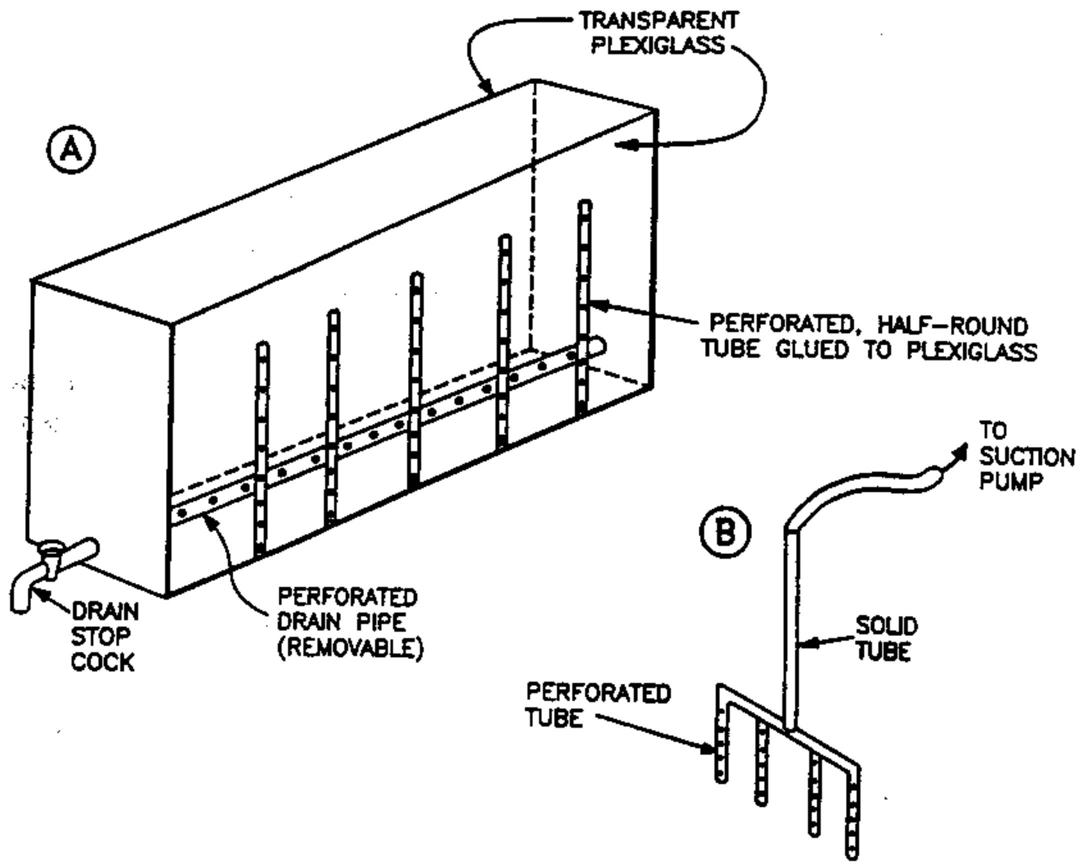

Fig. 3(A) Model constructed to simulate the hydrological regime beneath an island. (B) Branched pipe used to simulate a tree.

water was present. Water was then removed via the 'tree' until only a small quantity of surface water remained. Water level was restored using water to which fluorescein dye had been added. Once equilibrium was achieved, water was again removed via the 'tree'. This was repeated 30 times. The movement of the dyed water into the sand was tracked with the aid of a fluorescent lamp. To further elucidate groundwater flow patterns, water containing potassium permanganate was injected into the sand against the Plexiglas wall and its movement tracked.

(3) The effect of periodic flooding on the groundwater regime beneath an island in which the water table drawdown results from removal via a deep aquifer. In this experiment, the drain was installed and the sand in the tank was shaped into a cross section through an island, with 'swamp' on both sides (Fig. 5). The water table was lowered by allowing water to flow out via the drain. Water containing fluorescein dye was then added to the swamp on both sides of the island to return the level to the high water mark. Water was then drawn off again via the drain. Ten cycles of draw-off and replenishment were carried out and the movement of the dye tracked.

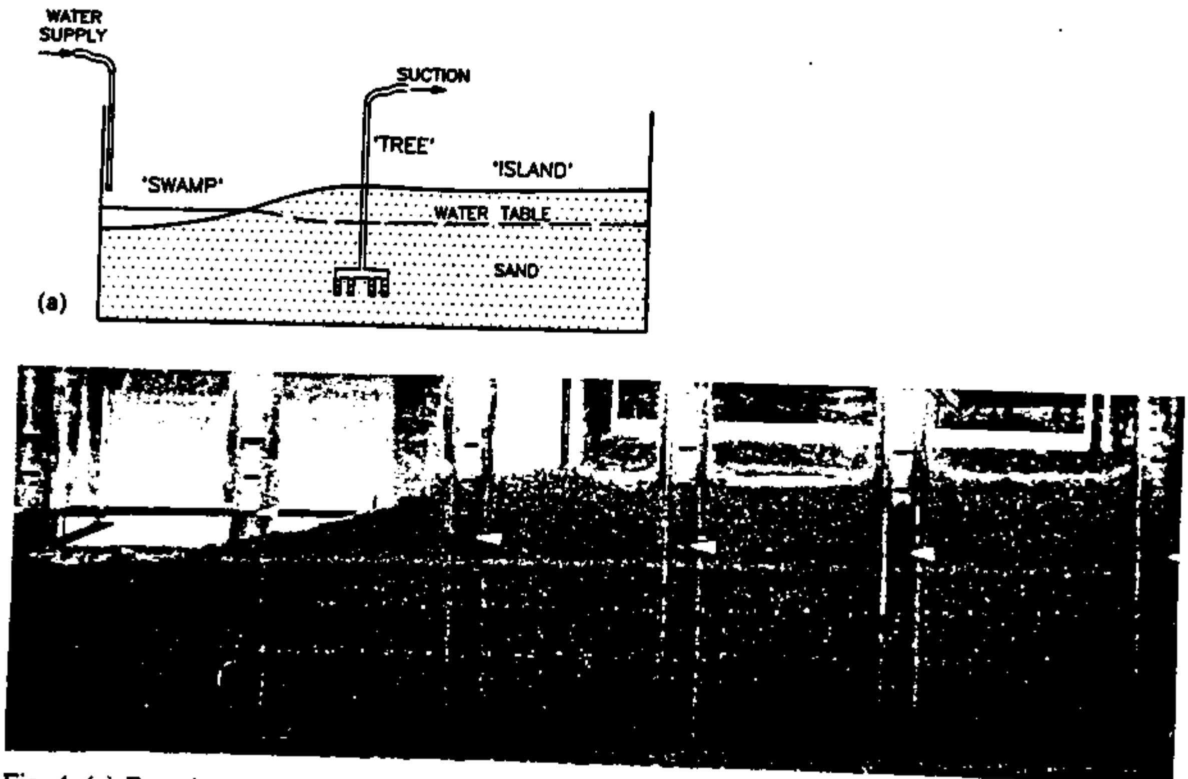

Fig. 4. (a) Experimental set-up used to model the effect of transpiration by trees at an island fringe. (b) Photograph of the experimental model with water inflow to the swamp equal to outflow via the 'tree'. The white arrowheads mark the position of the water levels across the tank.

4. Results

4.1. Topography and soil chemistry

Island soils consist of fine quartz sand with very fine calcite, amorphous silica and minor kaolin and are generally grey in colour near island fringes,

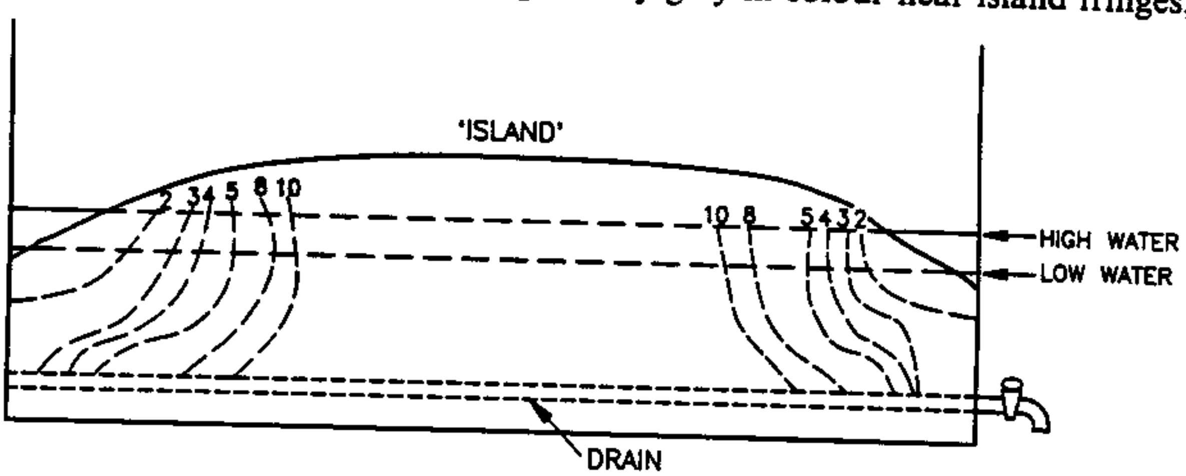

Fig. 5. Experimental set-up used to model the movement of swamp water beneath an island in which groundwater is drawn off via a drain, simulating a deep aquifer. The numbered lines show the progressive encroachment of swamp water beneath the island with successive flood cycles.

becoming yellow towards the centre. At depth, particularly around the fringes, the soils become nodular and in places are quite firmly cemented by calcite and amorphous silica. Colour changes to pale green with depth.

The margins of the island are slightly elevated relative to the interior (Fig. 6), with the interior being generally flat, although a small depression was developed along the traverse line, probably a former animal wallow pit. The depression contained perched surface water at the time of the initial survey in April 1991, but dried out during the year.

CaO and MgO contents of the soil are shown in Fig. 6. These occur as calcite. They are concentrated beneath the raised margins of the island, with MgO concentration peaking slightly inside the CaO peaks. Amorphous silica could not be quantitatively determined, but visual examination suggests that it closely follows calcium, reaching peak abundance slightly outside that of calcium. Apart from an isthmus linking the study island to a larger, adjacent island, the island is essentially circular (Fig. 2) and therefore the results shown in Fig. 6 suggest that calcite (and probably silica) occur in a toroidal distribution beneath the fringe of the island. This distribution is identical to that recorded beneath islands in the permanent swamp (McCarthy et al., 1991b, 1993).

4.2. Vegetation

The vegetation of the swamp at the island edge is a short (< 1 m), dense emergent grassland and sedgeland, dominated by the grasses *Leersia hexandra* and *Oryza sativa* (wild rice). Sedges include species of the genera *Cyperus*, *Pycreus* and *Eliocharis*. This gives way to a seasonally flooded lawn of *Cynodon dactylon*. Areas not flooded at all support a tall (> 10 m), dense fringe of broadleaved evergreen trees, including *Ficus natalensis* (strangler fig) and *Ficus sycamorus* (sycamore fig), the jackal berry *Diosphyros mespiliformis* and the African mangosteen *Garcinia livingstonei*. This gives way to a zone of deciduous trees including the knob-thorn *Acacia nigrescens*, the sausage tree *Kigelia africana*, and the Marula *Sclerocarya caffra*. To the interior of this is a zone of ivory palm, *Hyphaene ventricosa*, and this gives way to the short, hardy grass *Sporobolus spicatus*, which dominates the interior region of the island. The density of vegetation along transect is shown in Fig. 6.

4.3. The water table

The water table is depressed below the water level of the surrounding swamp (Fig. 7) and is relatively flat beneath the interior of the island, but gradients steepen under the margins where the water table slopes up to meet

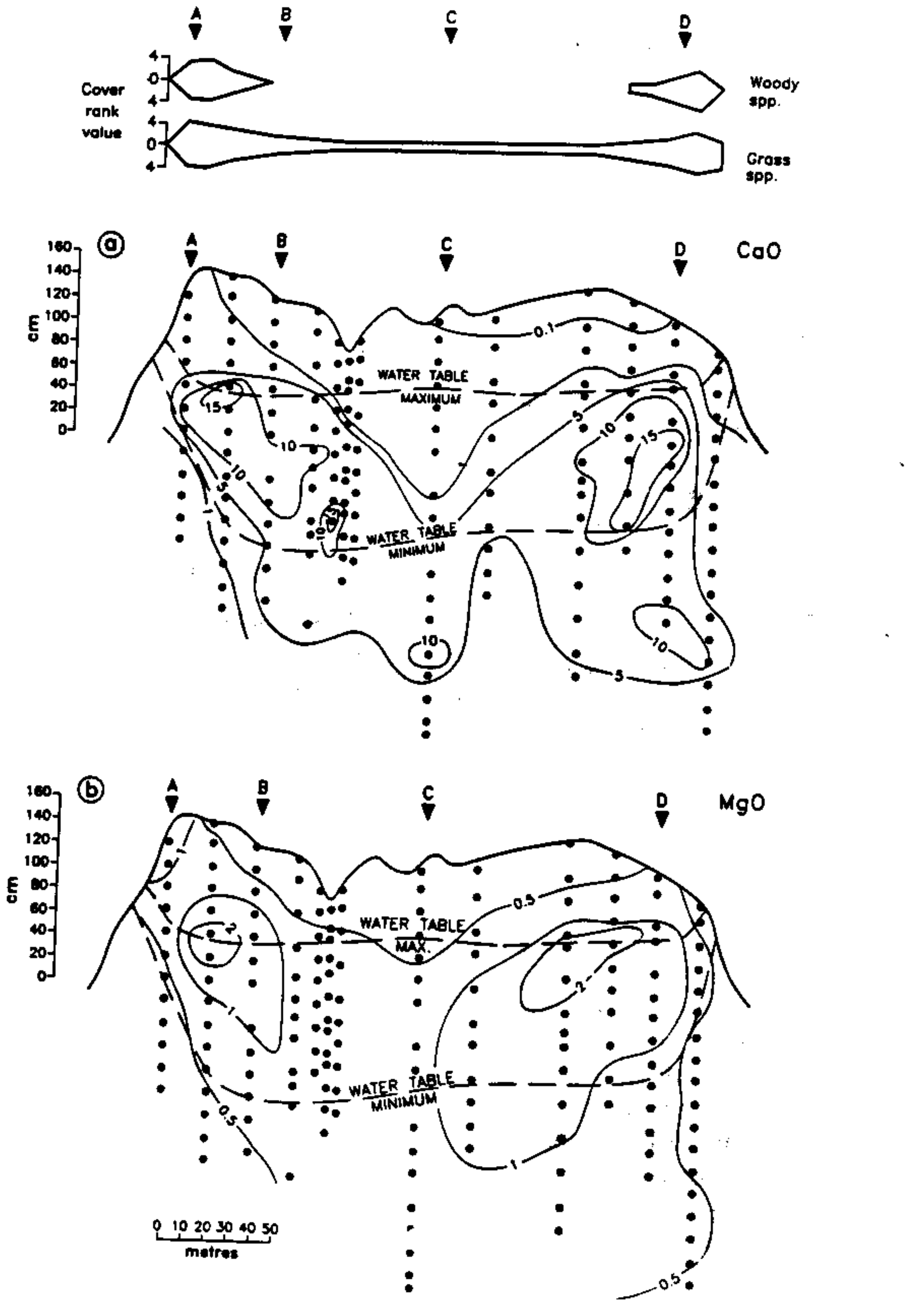

Fig. 6. Topography, vegetation density and soil CaO (a) and MgO (b) contents along the transect. Isopleths are in weight percent. Dots denote sample points.

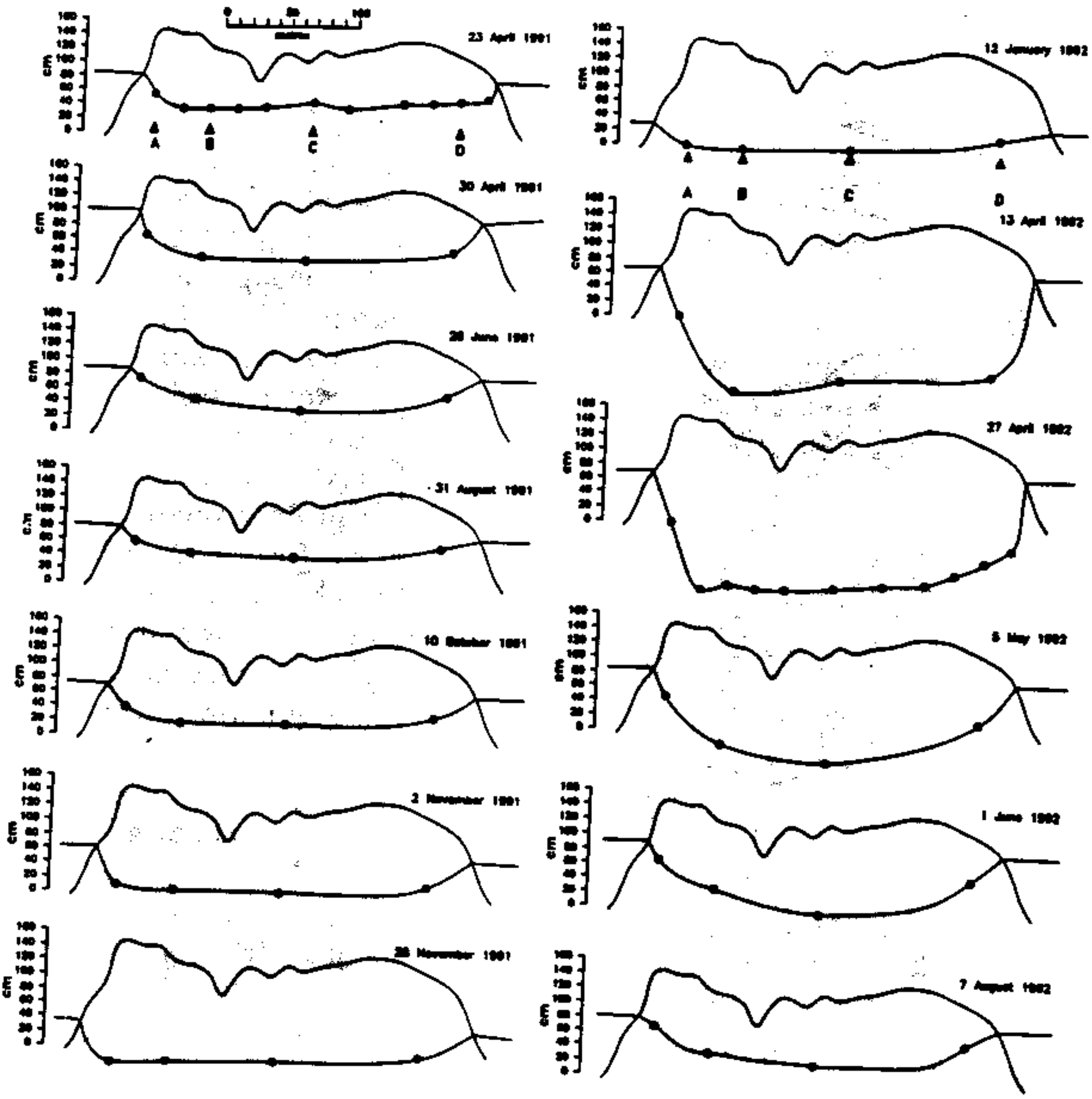

Fig. 7. Variation in the water table along the transect over the study period.

the swamp. The water table falls as the flood stage in the surrounding swamp falls with the passing of the seasonal flood (Table 1 and Fig. 7; April 1991 to January 1992), the rate of fall being slightly faster on the left side of the transect where the vegetation is more dense. This results in a gentle slope towards the left end of the profile (Fig. 7; January 1992).

Unfortunately, no data were recorded between January and April 1992, during which time the swamp attained its lowest level. Nevertheless, it is evident that the swamp water level rises with the arrival of the seasonal flood, but the response of the groundwater is slow, resulting in very steep lateral gradients in the water table (e.g. Fig. 7; April 1992). The water table rises over several months and continues to rise even after the flood has started to recede (Fig. 7; June 1992 to August 1992). Movements of the water table are

Table 1

Topography, depths to water table and ground water conductivities over the study period

Location	Swamp	Site A	30	Site B	70	90	Site C	150	190	210	Site D	250	Date
Distance (m)			10	30	50	70	90	124	150	190	210	230	250
Elevation (cm)			64	60	40	32	8	28	34	54	48	32	8
Conductivity (mS cm^{-1})	0.12	0.92	8.13	11.3	44.4	7.41	12.3	39.5	14.2	11.2	5.4	0.68	24/4/91
Depth (cm)	–	96	112	87	84	54	65	83	92	90	69	44	
Conductivity	0.070	0.63	–	8.8	–	–	14.1	–	–	–	2.1	–	30/4/91
Depth	48***	90	–	91	–	–	79	–	–	–	71	–	
Conductivity	0.052	0.63	–	9.6	–	–	18.4	–	–	–	3.0	–	28/6/91
Depth	54	77	–	79	–	–	84	–	–	–	57	–	
Conductivity	0.060	0.70	–	11.3	–	–	30.8	–	–	–	2.6	–	2/8/91
Depth	50	74	–	72	–	–	73	–	–	–	47	–	
Conductivity	0.056	0.89	–	7.6	–	–	31.4	–	–	–	2.7	–	31/8/91
Depth	67	88	–	80	–	–	72	–	–	–	55	–	
Conductivity	0.085	0.64	–	11.0	–	–	30.6	–	–	–	2.3	–	10/10/91
Depth	82	110	–	107	–	–	95	–	–	–	86	–	
Conductivity	0.093	0.80	–	10.1	–	–	30.0	–	–	–	2.3	–	2/11/91
Depth	89	140	–	121	–	–	110	–	–	–	98	–	
Conductivity	0.093	0.76	–	10.2	–	–	30.3	–	–	–	1.9	–	28/11/91
Depth	125	168	–	141	–	–	117	–	–	–	119	–	
Conductivity	0.079	0.48	–	9.8	–	–	27.0	–	–	–	1.7	–	12/1/92
Depth	132	161	–	130	–	–	102	–	–	–	115	–	
Conductivity	0.15	0.51	–	20.5	–	–	20.5	–	–	–	1.8	–	13/4/92
Depth	86	150	–	236	–	–	205	–	–	–	200	–	
Conductivity	0.11	0.30	4.2	19.2	36.1	33.1	27.0	34.0	11.3	4.7	2.19	0.96	27/4/92
Depth	86	154	249	220	219	195	213	217	229	212	178	132	
Conductivity	0.096	0.57	–	14.8	–	–	25.2	–	–	–	2.0	–	5/5/92
Depth	67	111	–	151	–	–	164	–	–	–	108	–	
Conductivity	0.076	0.82	–	12.6	–	–	25.0	–	–	–	2.3	–	1/6/92
Depth	46	81	–	101	–	–	124	–	–	–	75	–	
Conductivity	–	0.88	–	11.4	–	–	25.3	–	–	–	2.6	–	7/8/92
Depth	68	80	–	91	–	–	99	–	–	–	61	–	

* Relative to an arbitrary datum.
** Depth below surface.
*** Relative to ground level at site A.

therefore slightly out of phase with flood stage. This is further illustrated in Fig. 8, which shows the movement of the water table and flood stage as a function of time. The water table at site A, closest to the island edge (Fig. 8(B)), most closely approximates the flood curve (Fig. 8(A)). Points most distant from the island edge (sites C and B; Fig. 8(C)), show a quite sudden inflexion as a result of the arrival of the flood, but this occurs some 3 months later than the onset of swamp level rise.

There is a substantial difference in the groundwater curves for the two flood seasons recorded in the data: the seasonal low in April/May 1992 was very much greater than for the corresponding period in 1991. The reason for this is probably the exceptionally wet December–January of 1991 (based on verbal communication with staff at the Lodge).

Rainfall during the monitoring period is shown in Fig. 8. The 42 mm recorded in October 1991 had no noticeable effect on the water table, but the December 1991 and January 1992 falls of 145 mm and 32 mm, respectively, produced a short-lived rise in the water table.

As the water table rises and falls it appears to undergo changes in shape. During the period in which the water table falls, it tends to be flat with a slight convexity towards the centre of the island (Fig. 7). However, during the rise of the water table (after April 1992; Fig. 7), it becomes distinctly concave.

The water table was also found to vary over the course of a single day as is illustrated in Fig. 9, where the water table elevation at 05:50 h is taken as datum and the relative change in elevation across the island over the daylight hours is shown. Maximum change occurred towards the edges of the island, where a 7 cm fall was recorded. The water table returned to its original position overnight.

4.4. Model experiments

4.4.1. Effect of transpiration on the water table

In this experiment, the water table beneath the 'island' was found to be lower than in the flanking 'swamp' (Fig. 4(B)). Moreover, the water table in the interior of the island was found to be virtually horizontal, with no cone of depression near the 'tree'.

4.4.2. Effect of periodic flooding on the water table during 'transpiration'

The water containing the fluorescein dye migrated rapidly from the swamp towards and slightly beyond the 'tree' (Fig. 10), after which no further migration occurred. Potassium permanganate dye introduced against the Plexiglas showed flow direction as indicated in Fig. 10: beneath the 'swamp', flow was downwards towards the 'island' fringe, while in the inter-

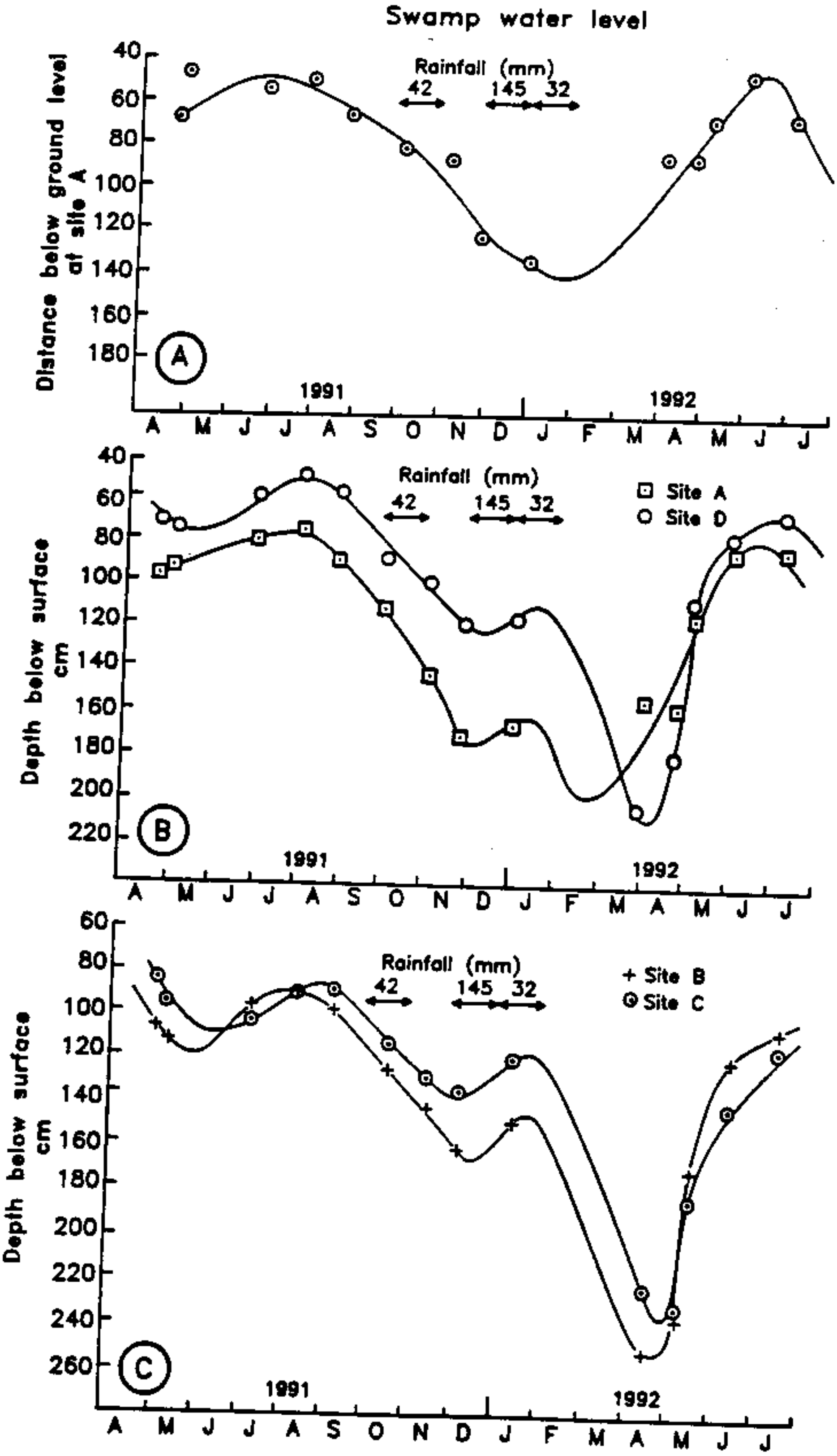

Fig. 8. Variation in flood stage and depth to the water table at the four monitoring sites as a function of time.

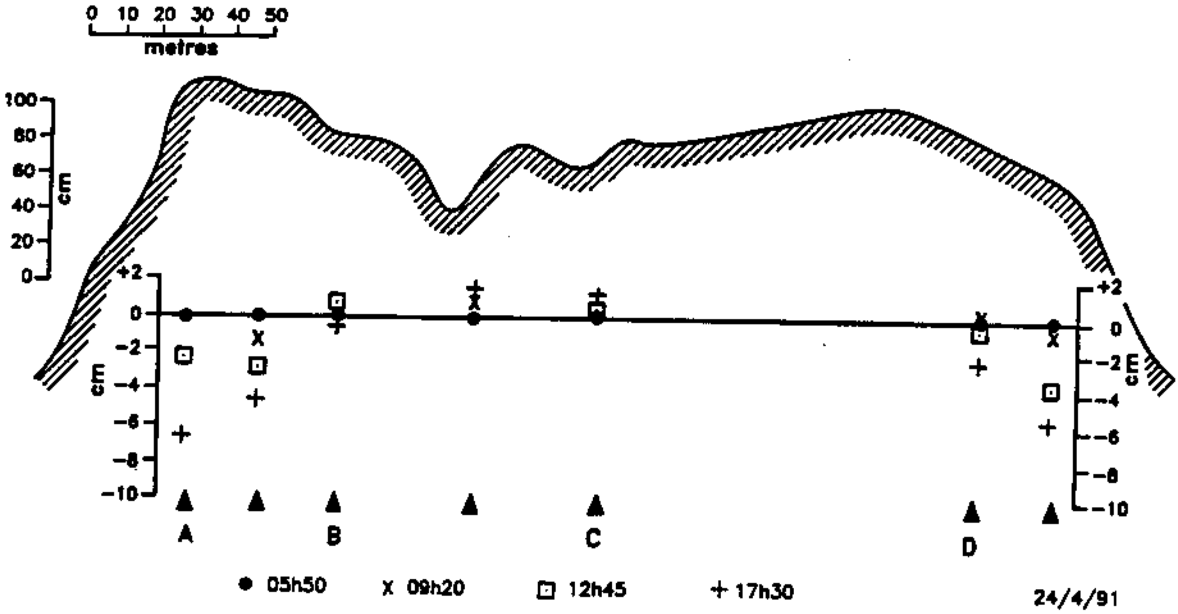

Fig. 9. Relative change in water table over the course of a day. The elevation of the water table at 05:50 h is used as reference.

ior of the 'island' movement was complex with both vertical and horizontal movement being recorded.

4.4.3. Effect of periodic flooding on an island in which groundwater is removed via a deep aquifer

In this experiment, the water table beneath the island was observed to rise as the 'swamp' level rose and there was a gradual encroachment of the dyed water under the 'island' fringes (Fig. 5).

4.5. Groundwater chemistry

Swamp water in the Okavango is generally of very low salinity (ca. 40 ppm

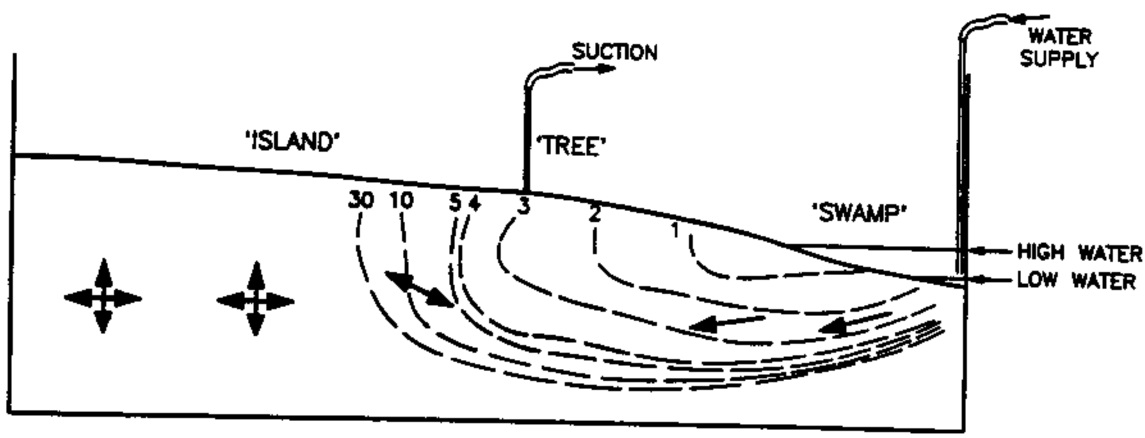

Fig. 10. Results of an experiment to examine the migration of swamp water beneath an island fringe where water is being removed by transpiration. The numbered lines show the movement of swamp water after successive flood events. Arrows show the flow directions of the groundwater.

Table 2
Representative analyses of swamp and groundwater

	Swamp		Groundwater				
	1	2	1	2	3	4	5
Ca mg l^{-1}	8	8	29	7	3	< 1	< 1
Mg	2	2	35	6	6	< 1	< 1
Na	6	8	35	1600	3800	16000	18000
K	7	6	8	182	322	980	1390
SiO_2	47	44	130	120	80	2	< 1
HCO_3^-	52	53	575	3519	7464	22049	21494
CO_3^{2-}	0	0	49	374	1241	8571	12962
Conductivity (mS cm^{-1})	0.11	0.092	0.32	2.19	11.6	34.0	36.1

TDS; Hutton and Dincer, 1976; Sawula and Martin, 1991; McCarthy et al., 1991b) and is bicarbonate dominated. However, salinities of groundwater beneath islands have been found to be high, as much as three orders of magnitude greater than swamp water (McCarthy et al., 1991b, 1993). The phenomenon can also be seen in the chemical data obtained in this study (Table 2).

Conductivity of groundwater, a measure of TDS, is shown in Fig. 11 and Table 2, and rises from the margins of the island towards the centre. At the commencement of the study in April 1991, a local conductivity low was found near the island centre, but this disappeared over the year. Its presence is ascribed to rainfall infiltration during the wet summer of 1990/1991 preceding the study. Salinity gradients tend to be steep near the margins of the island, but flatten towards the island centre. No major changes in average salinity levels were recorded during the study period. The fact that saline groundwater is centred beneath the island suggests that there is no significant lateral groundwater flow.

Eugster and Jones (1979) have shown that the chemical evolution of groundwater can be conveniently portrayed using binary diagrams in which the abscissa is a conserved element in the water system. The conserved element chosen in this study is Na (McCarthy et al., 1991b) and plots of this against SiO_2, Ca, Mg and K are shown in Fig. 12. Included for reference are the best fit lines for Okavango groundwater from the data of McCarthy et al. (1993) from islands in the permanent swamps. The groundwater chemistry of the present study conforms with that recorded by McCarthy et al. (1993).

The inflexion points in the case of Ca and Mg reflect the onset of calcite precipitation, while the lower inflexion point for SiO_2 represents the saturation point of amorphous SiO_2. The reference line in the case of K

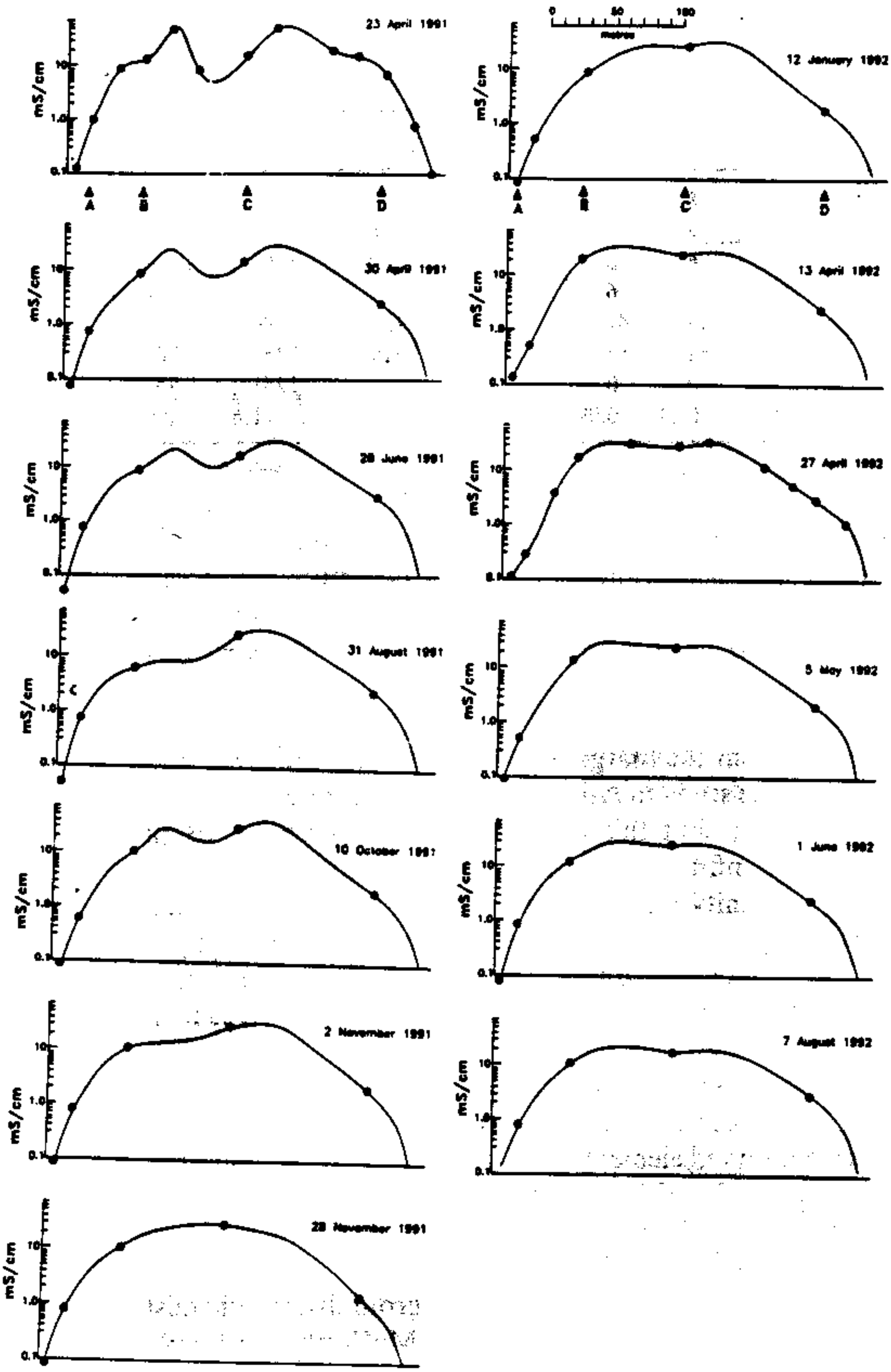

Fig. 11. Conductivity of groundwater along the transect over the study period.

shows no inflexion, indicating that the solutions do not saturate in a K-bearing phase. However, the slope of the line is less than unity, which has been interpreted as indicating continuous abstraction of K from solution, probably as a result of K feldspar formation (McCarthy et al., 1991b).

Groundwater samples collected at 0.4 m, 0.6 m, 1.0 m and 1.5 m below surface at site B all showed the same conductivity, indicating the absence of vertical gradients in chemistry at least over this depth range.

5. Discussion

5.1. Fluctuations of the water table

The water table beneath the island is always lower than surrounding swamp water level, irrespective of flood stage (Fig. 7). Gradients on the water table are steepest under the fringes of the island. The water table in these fringe areas is also subject to diurnal fluctuations (Fig. 9) while such fluctuations in the island centre are small, indicating that this is not a tidal effect (e.g. Bredehoeft, 1967). These fringe zones are most heavily vegetated (Fig. 6(a)) and we attribute these diurnal fluctuations to the effect of transpiration. The fact that the water table beneath islands is lower than the water surface of the surrounding swamps must also be a result of transpiration. The depression of the water table creates a pressure head which ensures continuous inflow of water from the swamp under the island fringe.

Experiments with the model confirmed that water abstraction via a 'tree' beneath the island fringe produced a lowered water table beneath the island (Fig. 4(b)). Normally, removal of groundwater in this way would produce a cone of depression, but as there is no reservoir in the interior of the island, draw-down is asymmetrical. In effect, the lowered water table beneath the entire island in the study area can be considered as a draw-down created by the ring of fringing trees.

As the flood stage falls, the rate of supply of swamp water declines and the water table falls. Because of the low vegetation density in the central region of the island, the water table in this region evidently falls more slowly, creating a slight convexity in the water table surface (Fig. 7). The more saline water beneath the centre of the island may tend to spread laterally at this stage, possibly accounting for the rapid rise in conductivity at site B during the period January to April 1992 (Table 1).

With rise in the flood stage, the rate of inflow of swamp water increases and the water table begins to rise again. This rise is evidently not accomplished by swamp water simply flowing laterally beneath the island down the water table gradient. If such a process occurred, seasonal dilution of the saline ground-

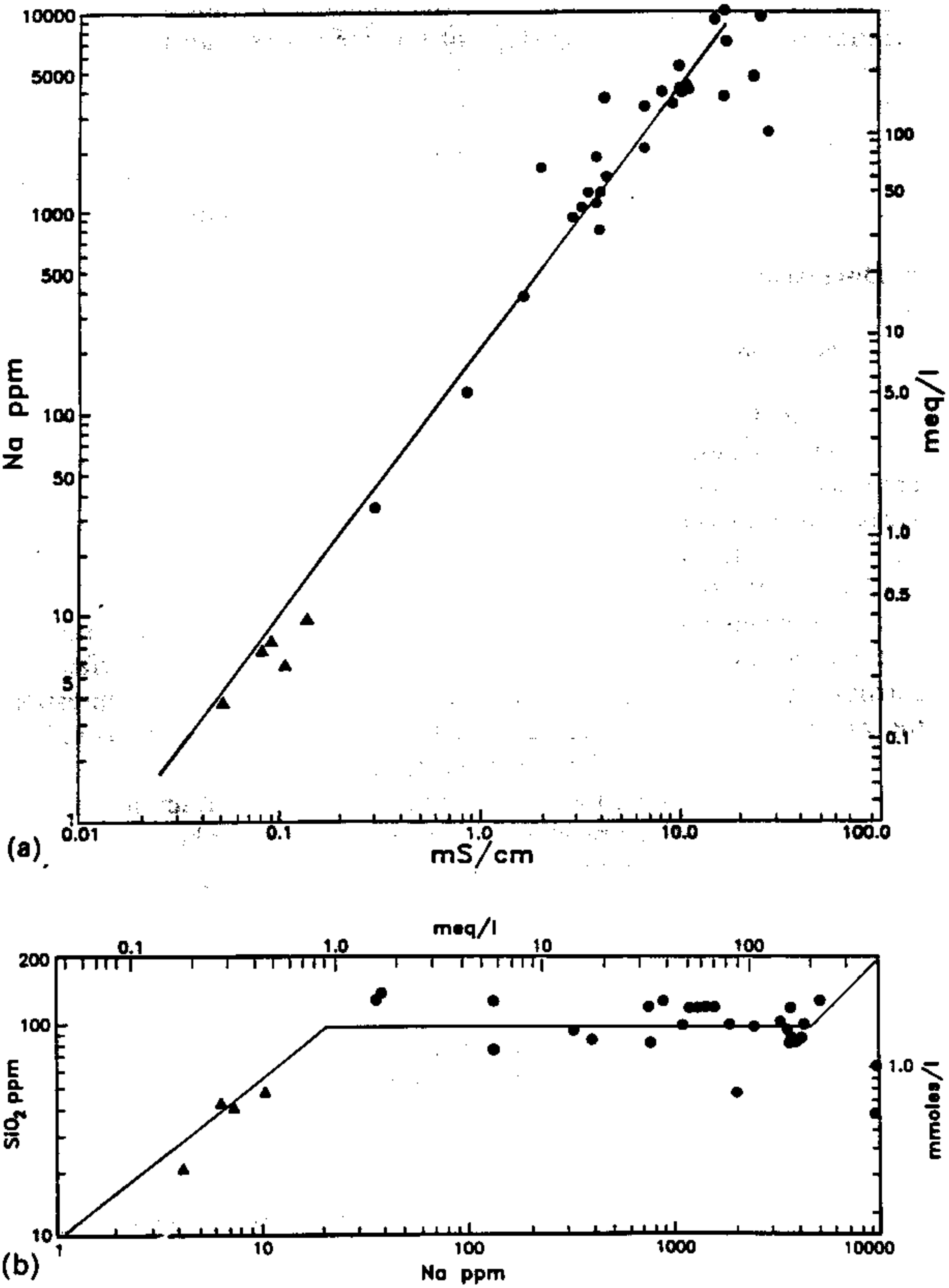

Fig. 12. Variation in conductivity, (b) SiO_2, (c) Ca, (d) Mg, and (e) K as a function of (a) Na in ground and surface waters from the study area. The solid lines show the variation in groundwater chemistry in the permanent swamps (from McCarthy et al., 1993).

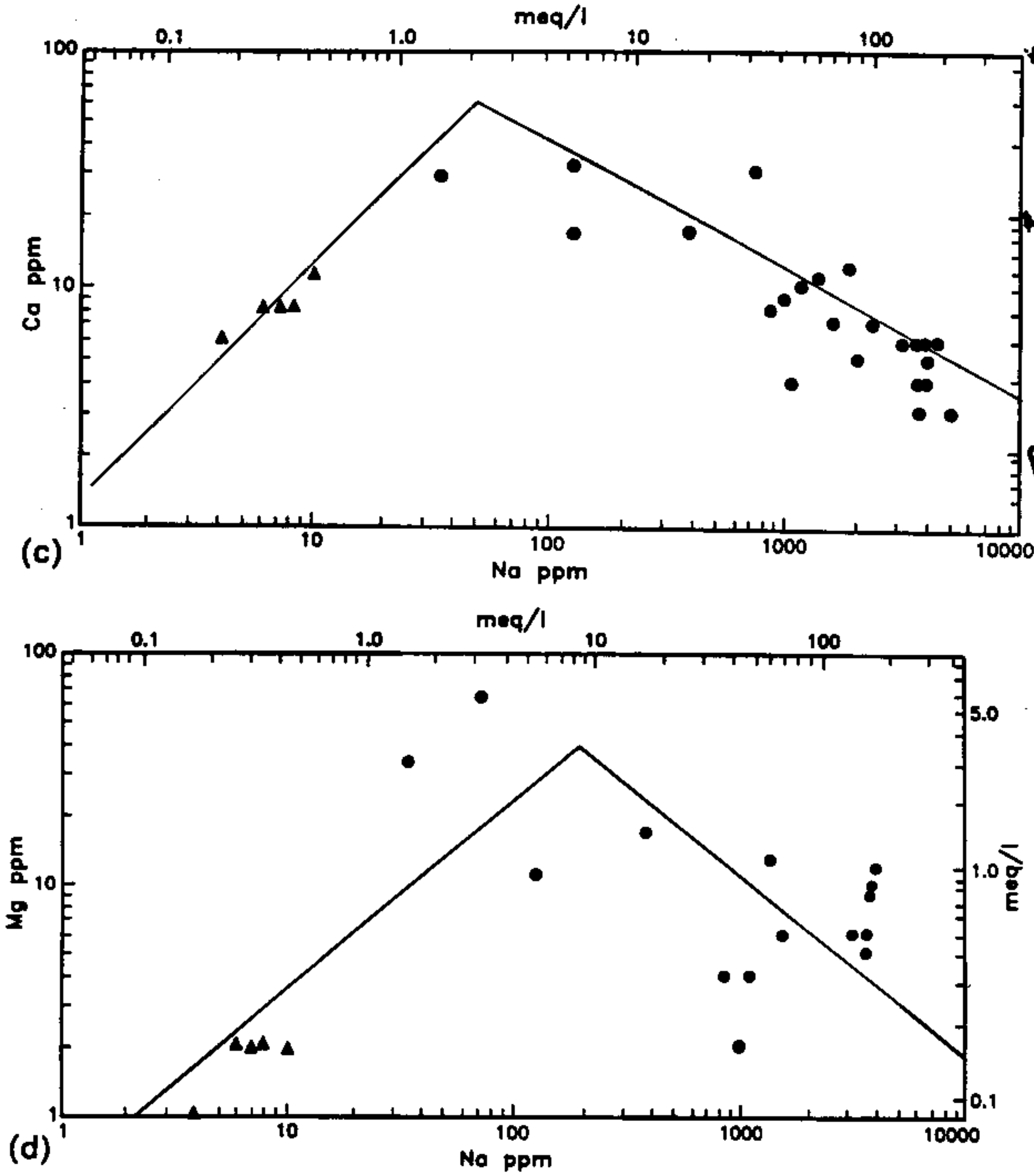

Fig. 12. Continued.

water beneath the island centre would occur and would have been detected. Moreover, this would result in vertical concentration gradients in the groundwater, which were also not detected. Rather, it appears that the pore pressure in the groundwater beneath the island is increased by the arrival of the flood and the water beneath the island rises as a result. Therefore, the saline water beneath the island centre simply oscillates vertically in response to seasonal fluctuations in flood stage and no dilution occurs.

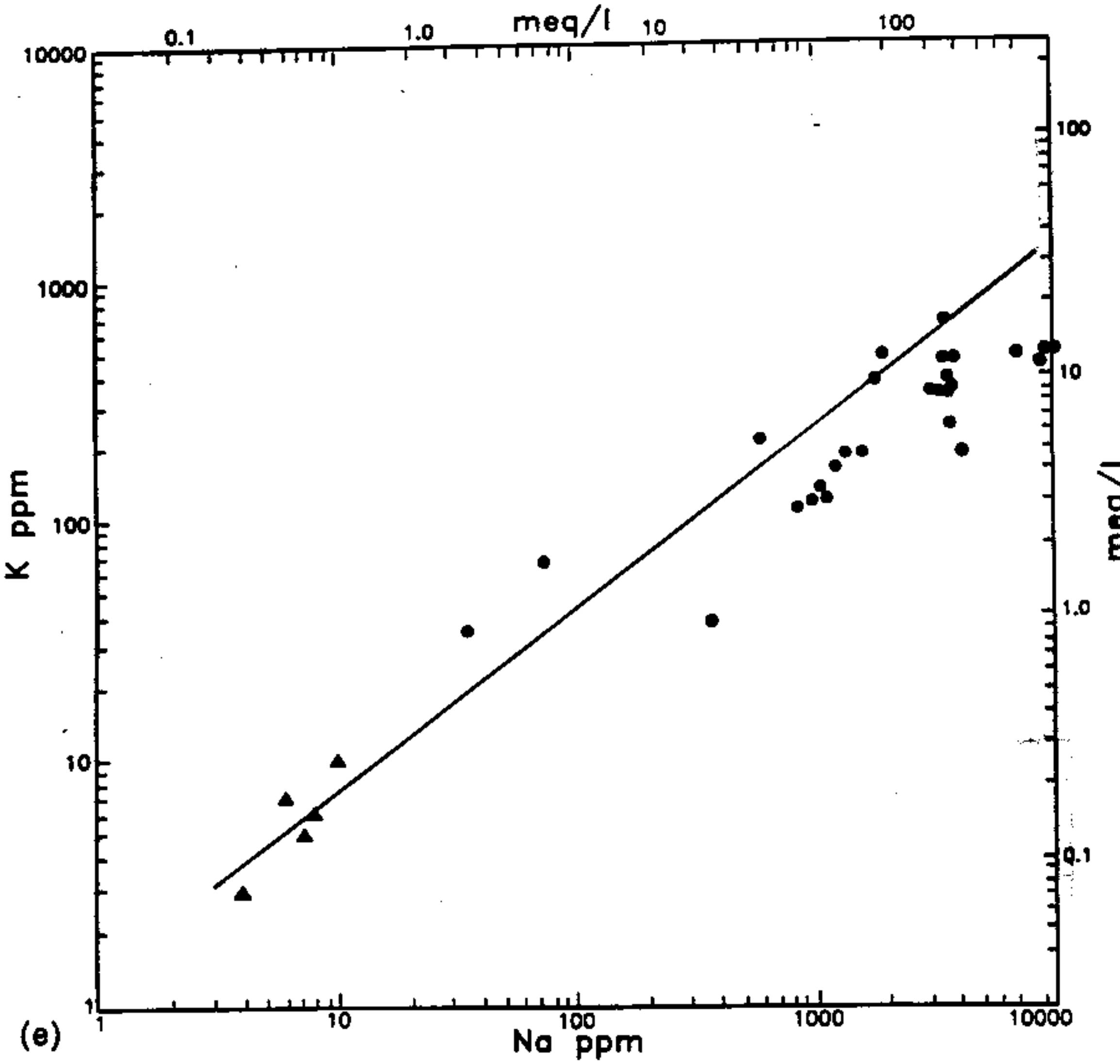

Fig. 12. Continued.

This is confirmed by experiments with the model where it can be seen that the extent of influx of water beneath an island from the sides is limited, irrespective of whether seasonal lowering of the water table is caused by draw-off via a deep aquifer (Fig. 5) or by the marginal vegetation fringe (Fig. 10).

5.2. Chemical gradients and vegetation zonation and cover

The wooded fringe areas of the island, where most of the transpiration occurs, are characterized by steep concentration gradients (Fig. 11). Plants, especially the large, broad-leaf, evergreen trees which characterize the island fringes, transpire water but leave dissolved solids behind, resulting in a salinity increase. As water slowly migrates laterally from the swamp through this fringe it becomes progressively more saline. The increase in dissolved solids results in saturation, firstly in silica and then calcite (Fig. 12), which precipitate in the island fringe (Fig. 6). The distribution of CaO in the soils in relation to high and low water table positions (Fig. 6(a)) suggests that most of this precipitation occurs during rising and high water level. The slight offset of MgO relative to CaO is attributed to the slightly lower partitioning of MgO into calcite relative to Ca (McCarthy et al., 1993). The precipitation of these minerals in the soils results in volume expansion (McCarthy and Metcalfe, 1990), giving the island its characteristic raised margin.

At the time of the initial survey (April 1991), soils on part of the poorly vegetated, central region of the island were covered by a thin layer of trona. This is the result of evaporation of saline groundwater brought to surface by capillary rise (McCarthy et al., 1986). This phenomenon is most pronounced during the dry winter months, when the water table is at its highest, and must also contribute to the very high salinities observed beneath the island centre.

The marginal salinity gradient in turn results in the species zonation evident on the islands. The distribution of woody species reflects their groundwater salinity tolerances, whereas the distribution of shallow rooted, herbaceous species (including grasses) reflects their soil salinity tolerances, particularly to trona (Ellery et al., 1993; McCarthy et al., 1993). In areas where trona is present as an efflorescent crust, even the hardy species, *Sporobolus spicatus*, may disappear.

During fall of the water table, there is some indication of outward movement of the saline water. This process must enhance the salinity gradient around the island fringe and inevitably further compress the vegetation fringe. Nevertheless, groundwater beneath the island centre must act as a sink for highly soluble salts (mainly $NaHCO_3$; Table 2) and concentrations will increase with time. Lateral spreading of this water during falling flood may ultimately destroy the vegetation fringe completely. This would only occur in the seasonal swamps, where fluctuations in the water table are large.

5.3. The effect of rainfall

Rainfall was abnormally low during the study period, so its full impact cannot be assessed properly. However, the relatively good falls of December 1991 caused a noticeable rise of the water table (Fig. 8). Moreover, the relatively high rainfall of the summer preceding the study may have been responsible for the irregular conductivity profile at the onset of the study (Fig. 11).

Rainfall is a potentially important agent in groundwater evolution. During the long, dry winter months, groundwater level is at its maximum (Fig. 7) and capillary evaporation causes the accumulation of soluble salts (mainly trona) on surface in the centre of the island. This is enhanced by the lack of vegetation in this region. Trona is dissolved by rainwater in the summer and as there is virtually no runoff because of the raised margins of the islands, most of the salts are returned to the groundwater. As evapotranspiration exceeds rainfall by at least a factor of three (Wilson and Dincer, 1976), there is a net accumulation of salts in the groundwater beneath the island centre.

5.4. Island hydrology

The hydrology of an island fringe zone is summarized in Fig. 13(A). In region X, water flow is continuous and unidirectional and the water is continually fresh (Fig. 13(B)). Beneath the island centre, seasonal changes in water level are accommodated by change in shape of the water volume: ABCD at high water changes to abCd at low water, with area (volume)

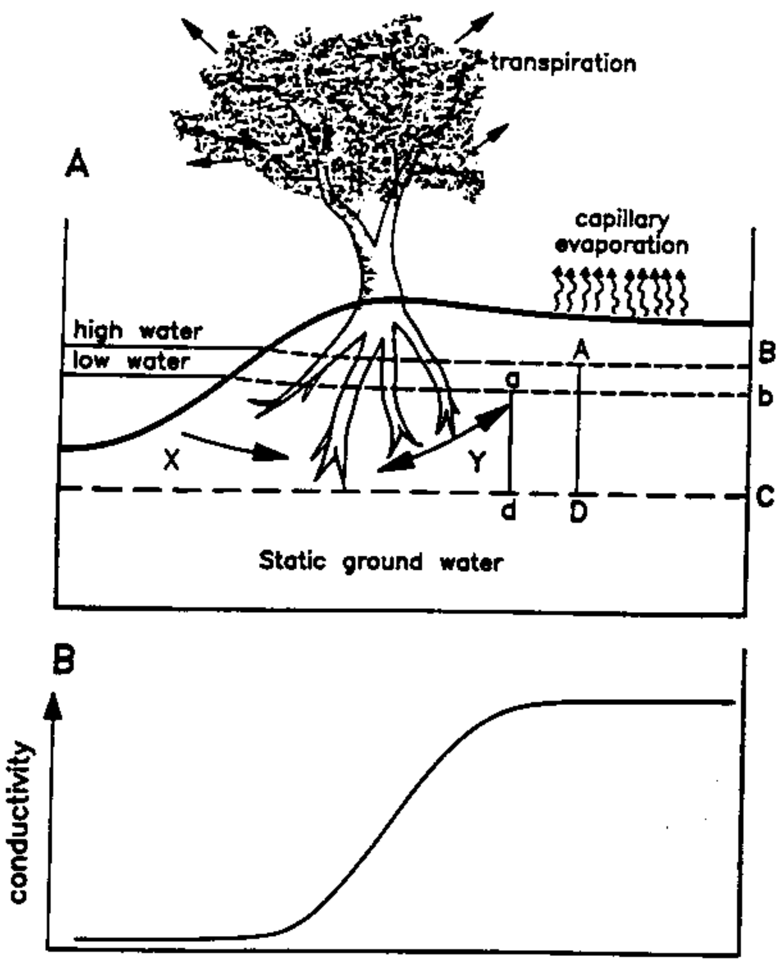

Fig. 13. Schematic diagram summarizing (A) the hydrology of an island fringe and (B) the resulting variations in groundwater conductivity. See text for details.

remaining constant, although there is some loss, especially at high water, owing to evaporation from the capillary zone. Salts which accumulate on surface as a result are returned to the groundwater during the rainy season. There is a steady increase in salinity in the groundwater in this region. Region Y is a buffer zone, with flow direction depending on whether flood stage is rising or falling. Water in this region has a relatively long residence time and becomes highly processed by transpiration as a result, and hence shows a steep concentration gradient. Calcite and silica precipitate in this region. There is a continual leakage from zone Y into the central water volume beneath the island to compensate for evaporation loss from the island centre. A region of static groundwater probably exists below the root zone. The salinity of this deep water is not known. The water table beneath the island is depressed even at low water stage and therefore groundwater continues to flow towards the island throughout the year. Islands therefore act as sinks for salts dissolved in the swamp water.

6. Conclusions

Groundwater regime and chemistry beneath islands in the seasonal swamps of the Okavango fan are controlled by seasonal flooding and by island vegetation. Large evergreen trees on the islands act as transpirational pumps, removing water but leaving dissolved solids in the groundwater. This results in the precipitation and accumulation of less soluble compounds (mainly calcite and silica) around the island fringes, while the more soluble salts (mainly $NaHCO_3$) collect at the island centres. Seasonal flooding does not disrupt this pattern. Rise in flood stage increases pore water pressure in the groundwater and the saline groundwater beneath islands simply rises in response. There is therefore no influx of fresh flood water from the margins of the islands to dilute the saline groundwater. Rain falling on the island is only of transient importance because of the high evapotranspiration rate but it does result in recycling of soluble salts which are brought to surface by capillary action during the dry, winter months.

The accumulation of salts beneath islands destroys vegetation. This occurs initially in the interior of the island. However, outward migration of saline water during the seasonal fall of the water table will gradually compress the marginal vegetation fringe and will ultimately destroy it completely. The time required for this to occur is not known, but is probably of the order of hundreds of years (McCarthy et al., 1991b). The evapotranspirational loss from islands is ecologically important because it localizes salt accumulation to specific groundwater regions, minimizing the environmental impact of saline accumulations.

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